Circularly Polarized Electrically Small Antennas for Emerging Wireless Applications

LIN Wei and Richard W. Ziolkowski
Global Big Data Technologies Centre
University of Technology Sydney
Ultimo NSW 2007, Australia
Wei.Lin@uts.edu.au, Richard.Ziolkowski@uts.adu.au

TANG Ming-Chun
College of Communication Engineering
Chongqing University
Chongqing, 400044, China
tmc_212@163.com

***Abstract*—This paper introduces three circularly-polarized (CP) electrically small antennas for emerging wireless applications including wireless power transfer (WPT), Internet-of-Things (IoT), and Device-to-Device (D2D) communications in future fifth generation (5G) systems. First, an electrically small Huygens CP (HCP) antenna operating at L-band frequencies is presented that is facilitated by two near-field resonant parasitic (NFRP) elements, a crossed Egyptian axe dipole (EAD) pair and a crossed capacitively loaded loop (CLL) pair. The HCP antenna is electrically small (ka = 0.73), low profile (~ 0.04λ_0), and has decent cardioid-shaped radiation patterns with a broad half power beamwidth (>120°). It is attractive for many WPT and body-centric wireless sensor network applications. Second, with the rapid development of 5G wireless networks, a corresponding 28 GHz electrically small HCP antenna is reported. The overall size of this antenna is only π (1.5)^2 × 1=mm^3 (ka = 0.94), which can be readily integrated into the various compact platforms anticipated for 5G IoT devices. Third, unlike the above two antennas that radiate uni-directional patterns, a compact 28 GHz omni-directional CP (OCP) antenna is presented for D2D communications in future 5G systems. It is electrically small (ka = 0.95), easy to fabricate, and its performance characteristics cover the entire FCC-specified 5G, 27.5 to 28.35 GHz band.**

Keywords*—*Circular polarization, electrically small antennas, Huygens sources, omni-directional, near-field resonant parasitic elements, next generation (5G) wireless systems

I. INTRODUCTION

Electrically small antennas (ESAs) have drawn much attention along with the rapid development of modern and next generation (5G) wireless systems. ESAs are highly desired to be integrated into the compact platforms of wireless devices anticipated for the Internet-of-Things (IoT) devices in future 5G systems [1]. Moreover, circular polarization (CP) has the merit of polarization purity that is attractive for many wireless applications to avoid polarization mismatch issues [2] – [3]. In this paper, we will introduce three of our recent research works pertaining to innovative electrically small CP antennas for emerging wireless applications. They include an L-band electrically small Huygens CP (HCP) antenna for wireless power transfer (WPT) applications; a 28 GHz electrically small HCP antenna for 5G IoT applications; and a 28 GHz electrically small omni-directional CP (OCP) antenna for Device-to-Device (D2D) communications in 5G wireless systems.

II. ELETRICALLY-SMALL HUYGENS CP (HCP) ANTENNA

The design concept and implementation of an electrically small Huygens linearly-polarized (HLP) antenna were successfully demonstrated in [4] and [5], respectively. However, for applications like wireless power transfer (WPT) and satellite communication systems [6], circular polarization is preferred. In this section, we will present the first realized electrically small HCP antenna operating at L-band. It is illustrated in Fig. 1. It has been engineered for WPT applications in wireless sensor networks [7].

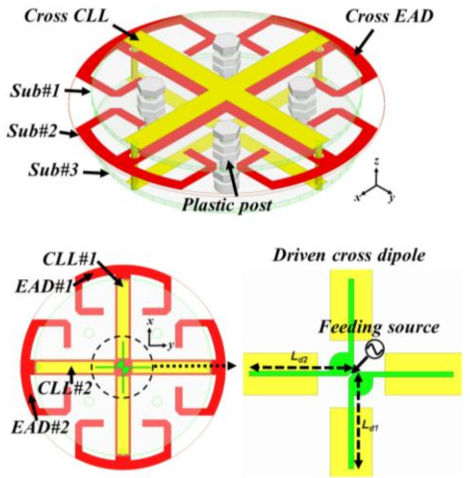
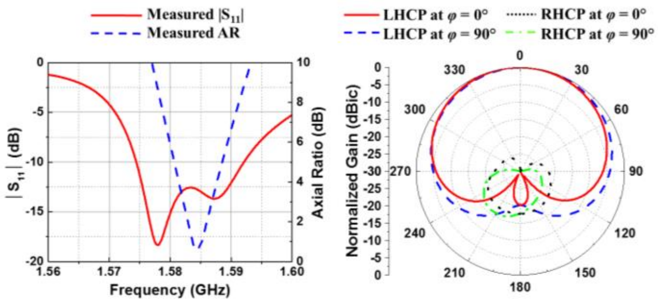


Fig. 1 Electrically small Huygens CP (HCP) antenna for wireless power transfer (WPT) applications.

The HCP antenna intrinsically combines two near-field resonant parasitic (NFRP) elements, a crossed Egyptian axe dipole (EAD) pair and a crossed capacitively loaded loop (CLL) pair, together with a driven dipole element. These two pairs of mutually orthogonal electric and magnetic dipoles have been organized into the entity shown in Fig. 1. The HCP antenna consists of three PCB boards, all made from Rogers^{TM} 5880 copper-cladded substrate. The cross CLL radiator has pieces printed on the top and bottom substrates (Sub#1 and Sub#3) which are connected by four vertical copper posts. The EAD radiator is printed on the middle substrate (Sub#2), which is sandwiched by the other two substrates. An unbalanced cross driven dipole element is designed to provide the requisite 90° phase difference between the two pairs of electric and magnetic dipoles to achieve the CP performance. The structure is compact; its overall volume is only $\pi\ (22.5)^2 \times 7.79$ mm^3 (ka = 0.73). It is more than 92 times and 88 times smaller than the previously reported HCP antennas in [8] and [9], respectively.



(a) (b)

Fig. 2 Measured results of the electrically small HCP antenna: (a) Measured $|S_{11}|$ and AR values as functions of the source frequency. (b) Measured radiation patterns at 1584 MHz.

The measured results exhibit very good Huygens CP radiation. As seen in the measured $|S_{11}|$ and axial ratio (AR) values as functions of the source frequency given in Fig. 2(a), the best CP radiation appears at 1584 MHz with only 0.57% frequency shift from the originally targeted 1575 MHz. The radiation patterns in Fig. 2 (b) exhibt excellent cardioid-shape with a broad beamwidth. In fact. its half power beamwdith is larger than 120° and its 3 dB AR beamwidth covers the entire upper half space. The measured realized RHCP gain is 2.7 dBic with a total radiation efficiency of 70%. Hence, having a small footprint and being lightweight, this HCP antenna is an ideal candidate for integration into sensors in a wireless network as an enabling WPT feature.

III. 28 GHz Eletrically Small HCP Antenna

The next generation 5G cellular networks are anticipated to be commercially available in 2020. A considerable number of investigations are ongoing currently for 5G wireless systems [10]. With the increasing demand for extremely large data exchange volumes and high data transfer rates, higher frequency, i.e., millimeter-wave, operation is expected to be applied in 5G devices. In [11], the 28 GHz band has been experimentally verified to be the suitable frequency carrier for 5G applications and the Federal Communications Commission (FCC) of the US has recently (July 2016) allocated the 28 GHz band for 5G systems [12]. With this background, we designed the 28 GHz electrically small HCP antenna shown in Fig. 3. Given its compact size and good performance characteristics, it is attractive for future ubiquitous 5G IoT devices [13].

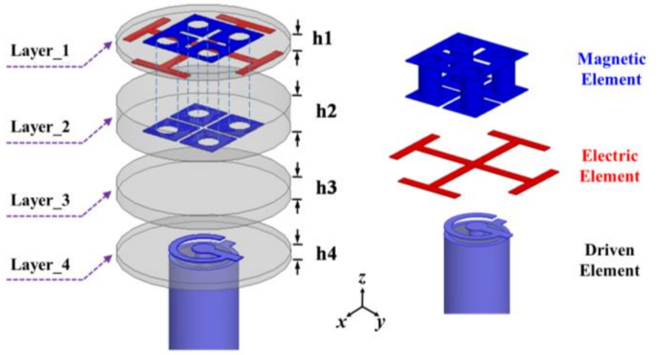
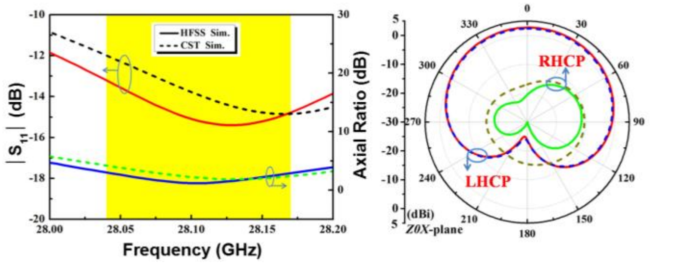


Fig. 3 28 GHz Electrically small Huygens CP antenna for 5G IoT applications.

The 28 GHz HCP antenna consists of three main parts: the magnetic element, the electric element, and the driven element. All of them are printed on Rogers^{TM} 5880 copper-cladded substrates, labeled as Layer_1 to Layer_4. Compared with the L-band HCP antenna, all of the NFRP and the driven elements have different configurations in this 28 GHz version. For example, the magnetic element consist of two CLLs in an orthogonal arrangement and the electric element is formed by a crossed I-shaped radiator. In addition, the driven element is a small open loop. The antenna is fed with a KTG 047-50 semi-rigid coaxial cable that has a 50Ω characteristic impedance and a 109 GHz cut-off frequency. The overall size of this antenna is only $\pi\ (1.5)^2 \times 1$ mm^3 (ka = 0.94), which can be readily integrated into the compact platforms anticipated for 5G IoT devices.



(a) (b)

Fig. 4 Simulated results of the 28 GHz electrically small HCP antenna from both HFSS and CST: (a) Simulated $|S_{11}|$ and AR values as functions of the source frequency. (b) Simulated radiation patterns at 28.105 GHz.

The simulated results from both HFSS and CST are shown in Fig. 4. The overlapped -10-dB impedance and 3-dB AR bandwidth from HFSS (CST) is 130 MHz, from 28.04 to 28.17 GHz (120 MHz, from 28.07 to 28.19 GHz) as observed in Fig. 4 (a). The minimum AR value is 1.18 dB (1.86 dB) at 28.105

GHz (28.14 GHz). Fig. 4 (b) presents the simulated radiation patterns at 28.105 GHz. It is seen that cardioid-shaped CP radiation patterns have been realized. The peak realized gain value is 2.03 dBic (2.82 dBic).

IV. 28 GHz Electrically small Omni-Directional CP (OCP) Antenna

In addition to the expected engagement of millimeter-wave operations, another evolutionary technology expected in future 5G systems is expected to be Device-to-Device (D2D) communications. In the 5G era, all IoT devices will be able to exchange data with any nearby device [14]. For such an application scenario, we have developed a 28GHz OCP antenna with compact size, high radiation efficiency, and decent bandwidth covering the 27.5 to 28.35 GHz band allocated for 5G applications [15].

The model of the 28 GHz electrically small OCP antenna is shown in Fig. 5, which is printed on a small piece of Rogers™ 6006 copper-cladded substrate. The overall size of the antenna disk is $\pi\ (1.5)^2 \times 1.2\ mm^3$ (ka = 0.95). From the simulation results, it is found that the operating bandwidth of the electrically small OCP antenna covers the entire 27.5 to 28.35 GHz band for 5G applications.

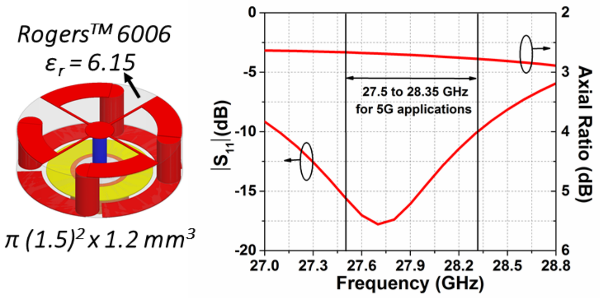


Fig. 5 28 GHz electrically small omni-directional CP (OCP) antenna for Device-to-Device (D2D) communications in future 5G systems.

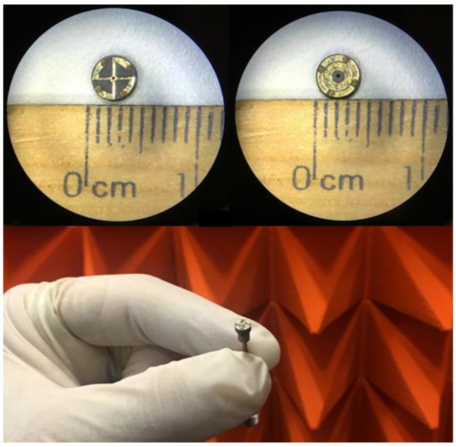


Fig. 6 Fabricated antenna prototype of the 28 GHz OCP antenna.

Fig. 6 shows the fabricated OCP antenna prototype and its images from a microscope. It is noted that for convenience of fabrication and assembly, we chose the commercially available Rogers™ 5880 substrate with the standard thickness of 1.575 mm for the final design. The final overall size of the OCP antenna is $\pi\ (2.0)^2 \times 1.57\ mm^3$, which is still compact and small enough to be embedded in future 5G IoT devices for D2D communications. The measured OCP antenna was fed by a coaxial cable. Two copper sleeve baluns were added on the coax to prevent any current leakage onto the outer conductor.

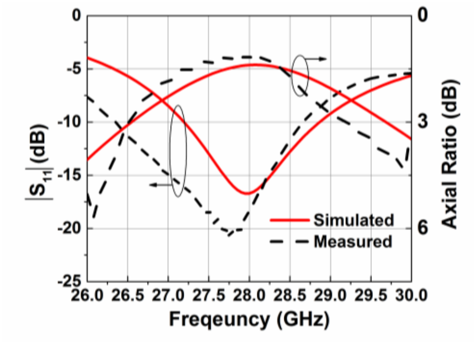
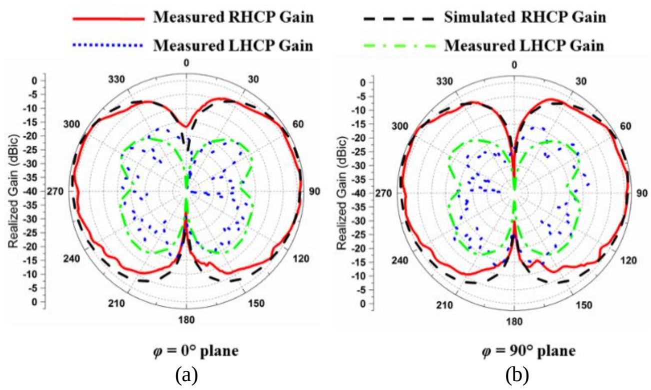
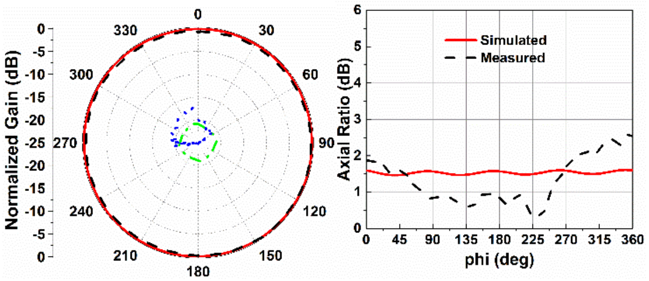


Fig. 7 Measured and simulated $|S_{11}|$ and AR values as functions of the source frequency.

Measured and simulated $|S_{11}|$ and AR values of the 28 GHz OCP antenna as functions of the source frequency are shown in Fig. 7. It is observed that the simulated and measured values are in good agreement with only a slight frequency shift. The measured overlapped impedance and AR bandwidth is 2.2 GHz from 26.5 to 28.7 GHz, which covers the entire 27.5 to 28.35 GHz band for 5G applications. Fig. 8 presents the measured and simulated realized gain patterns at 27.8 GHz where the AR value is the minimum. Quite decent OCP realzied gain patterns were obtained with the co-pol RHCP gain variation being less than 0.7 dB in the azimuth plane. Moreover, the radiation efficiency reaches 95%. This reported 28 GHz OCP antenna with its compact size and excellent radiation performance is an ideal candidate for the upcoming 5G wireless systems, specifically for D2D communication applications.





(c) (d)

Fig. 8 Measured results of the 28 GHz OCP antenna: (a) Measured realized gain pattern in the vertical φ = 0° plane at 27.8 GHz. (b) Measured realized gain pattern in the vertical φ = 90° plane at 27.8 GHz. (c) Measured realized gain pattern at the horizontal θ = 90° plane at 27.8 GHz. (d) Simulated and measured AR values in the horizontal θ = 90° plane at 27.8 GHz.

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